FINAL REPORT

TESTING OF THE INDAL 6400 VAWT STRUT MODIFICATION

RENEWABLE ENERGY BRANCH

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ABSTRACT

This report concerns the Indal Technologies 6400 series vertical axis wind turbine located at the Atlantic Wind Test Site on PEI. The operating history leading up to the fatigue failure of the blade is described as well as the design of the modifications and the subsequent testing and validation of the new design.

Test results indicate that the mathematical model predictions of the natural frequencies of the operating rotor agree well with experimental data. The data also confirm that the fatigue stresses adjacent to the strut connection have been reduced while those at the root connections have been slightly increased.

The fatigue life of the modified rotor is conservatively estimated to be 17 years.

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EXECUTIVE SUMMARY

This report covers the research and development program required to modify the Indal Technologies 6400 series 500 kW VAWT located in PEI at the Atlantic Wind Test Site (AWTS).

The modifications were required after experiencing a fatigue failure in the rotor blade. The intent of the modifications was to restore the machine to operational status and increase the resistance to fatigue. The machine design life of 20 years was the goal set for all major components.

The modifications to the VAWT were a departure from previous designs. The strut compliance was accomplished solely by flexing of the strut itself instead of by a mechanical spring and damper assembly. Additional local reinforcement of the blade was accomplished using structural adhesives bonding aluminum to aluminum.

The results to date have been very good. All the natural frequencies are within 5% of those predicted by the computer model, and worst case fatigue life predictions agree well with the design life goal.

The single I-beam strut assembly is considerably cheaper than the previous rigid strut with mechanical spring coupler. It is also much simpler since it has no moving parts to fail. The adhesive bonding of reinforcing plates on the blades adds cost, but adds considerably to the fatigue life.

One conclusion is that the strut could have been slightly stiffer since the critical area of the rotor is now the blade root. Future minor modifications should further improve the fatigue life.

1.0 INTRODUCTION

Indal Technologies Inc. has been developing the Darrieus Vertical Axis Wind Turbine since 1974 in close association with the Canadian National Research Council (NRC). The design and construction of a wind turbine is a considerable challenge. Very few other machines have to operate continuously in extremes of climate with a high degree of reliability and without the the benefit of close supervision. In addition, fatigue of components is a major concern. For example, the number of fatigue loading cycles experienced by a wind turbine in a life of 20 years greatly exceeds that expected for any aircraft.

In 1982 Indal Technologies began a program to create a commercial VAWT with a power rating of 500 kW. One of the first steps was to produce a small number of machines and operate these for several years to prove the design and to validate computer models.

One of the two machines tested was the 500 kW VAWT machine located at the Atlantic Wind Test Site (AWTS). This fully instrumented machine was purchased by the National Research Council and has been operated at the Atlantic Wind Test Site since September of 1984. Since the closing of the Energy Division of the National Research Council the Department of Energy, Mines and Resources (EMR) has assumed the NRC's role in administering the program.

The original rotor was designed for a 20 year life and fatigue samples simulating blade root connections and

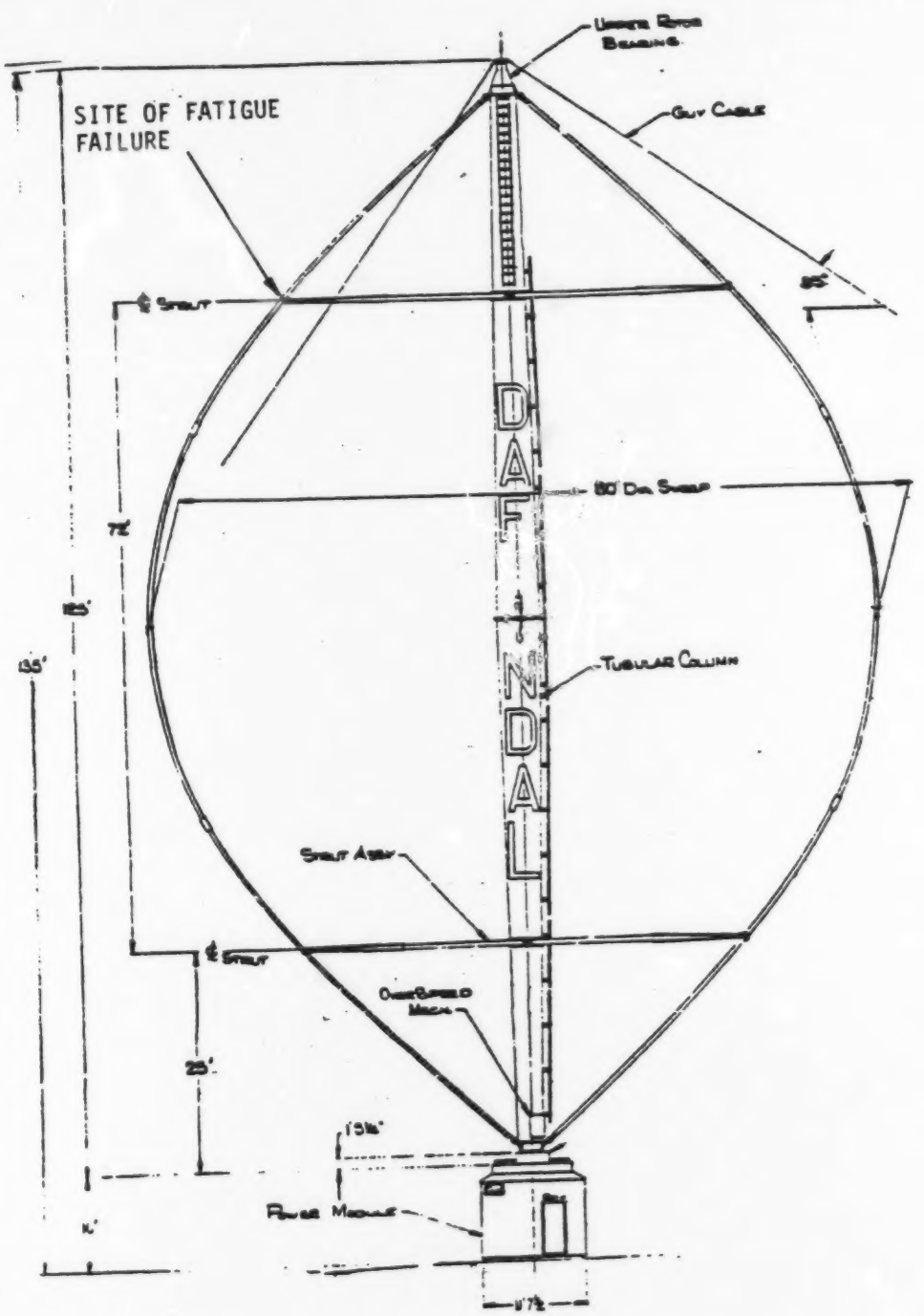
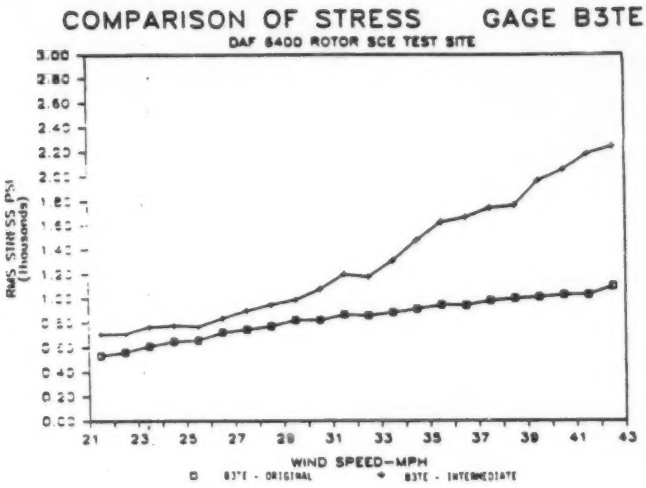
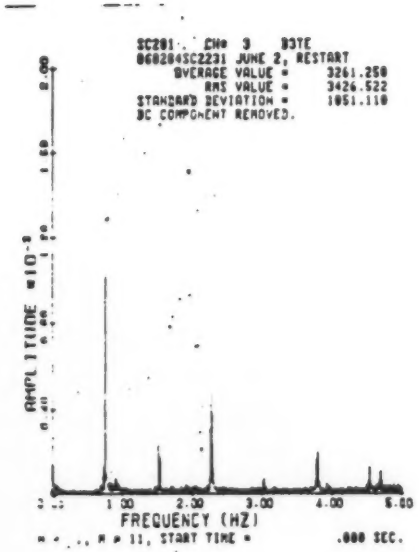
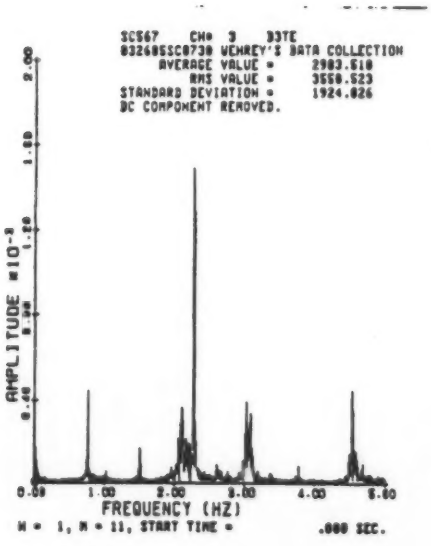


FIGURE 1





ORIGINAL CONFIGURATION



INTERMEDIATE CONFIGURATION

FIGURE 2

splices confirmed that this aim would be met. Difficulties were encountered, however, with the strut damper system which worked well but had an unacceptable failure rate. This led to the locking of the struts to simplify the design and enhance reliability.

Locking of the struts led to a reduction in strut compliance but this was compensated for by reballasting the blades. This was done by filling a second gallery in the blade extrusion with glass beads - a weight increase of 400 lb. per blade. This version of the rotor was named the "intermediate configuration".

Unfortunately the reballasted configuration exceeded the stress levels of the original design which had been confirmed in both computer modeling and field testing in PEI and at the Southern California Edison (SCE) test site. While the stress levels in the intermediate configuration were close to those in the original for wind speeds up to 25 mph (specifically at the A6 location), some rms stresses were increased by 70% at wind speeds of 45 mph.

Damage due to fatigue accumulated more quickly in the intermediate configuration because the predominant stresses occurred at 3 P (2.25 Hz) instead of at 1 P (.75 Hz) as in the original design (see Figure 2).

In November 1985 a fatigue failure occurred at the attachment point of the upper strut and the blade. This joint is shown in Figure 1. The failure resulted from local fatigue damage and was reported in NRC Structure Laboratory Report LTR-ST-1582.

The NRC report on the failure pointed to several contributing factors: intergranular corrosion, fretting, and sharp edges due to machining. All of these factors were exacerbated by the high net stresses experienced by the intermediate configuration.

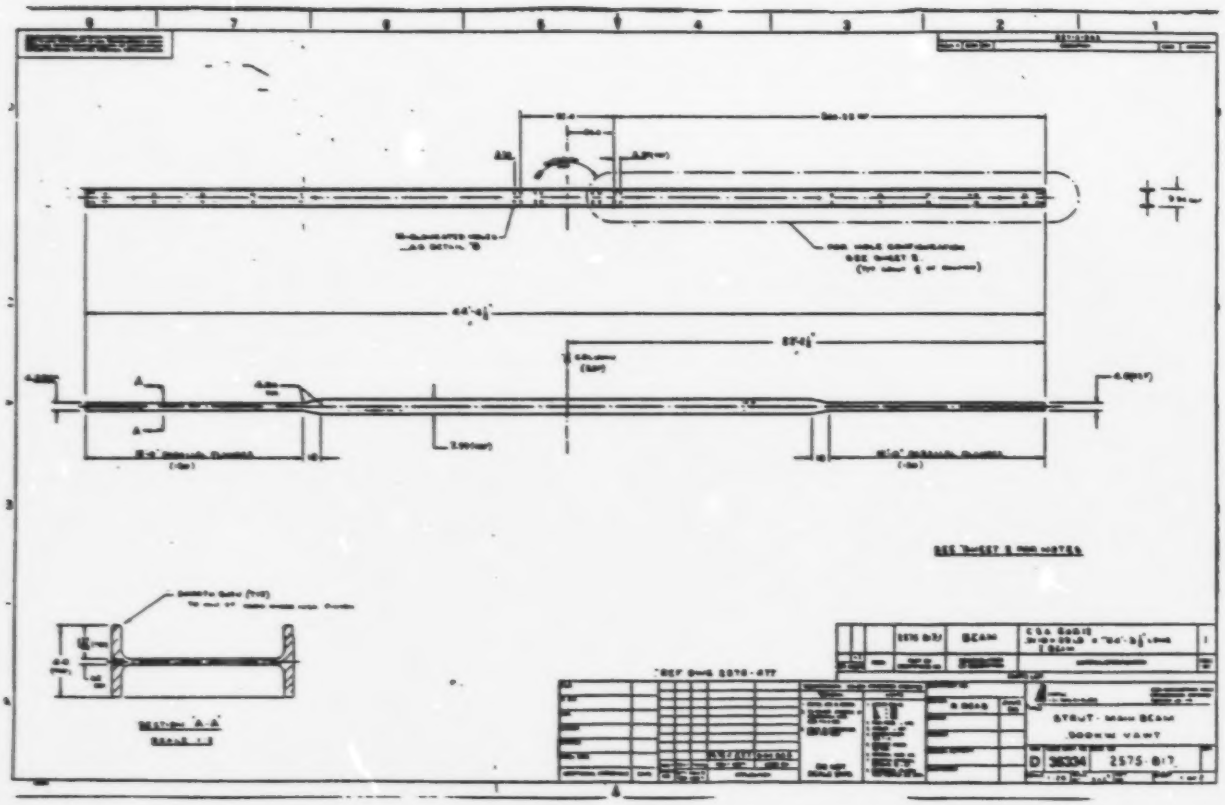


FIGURE 3

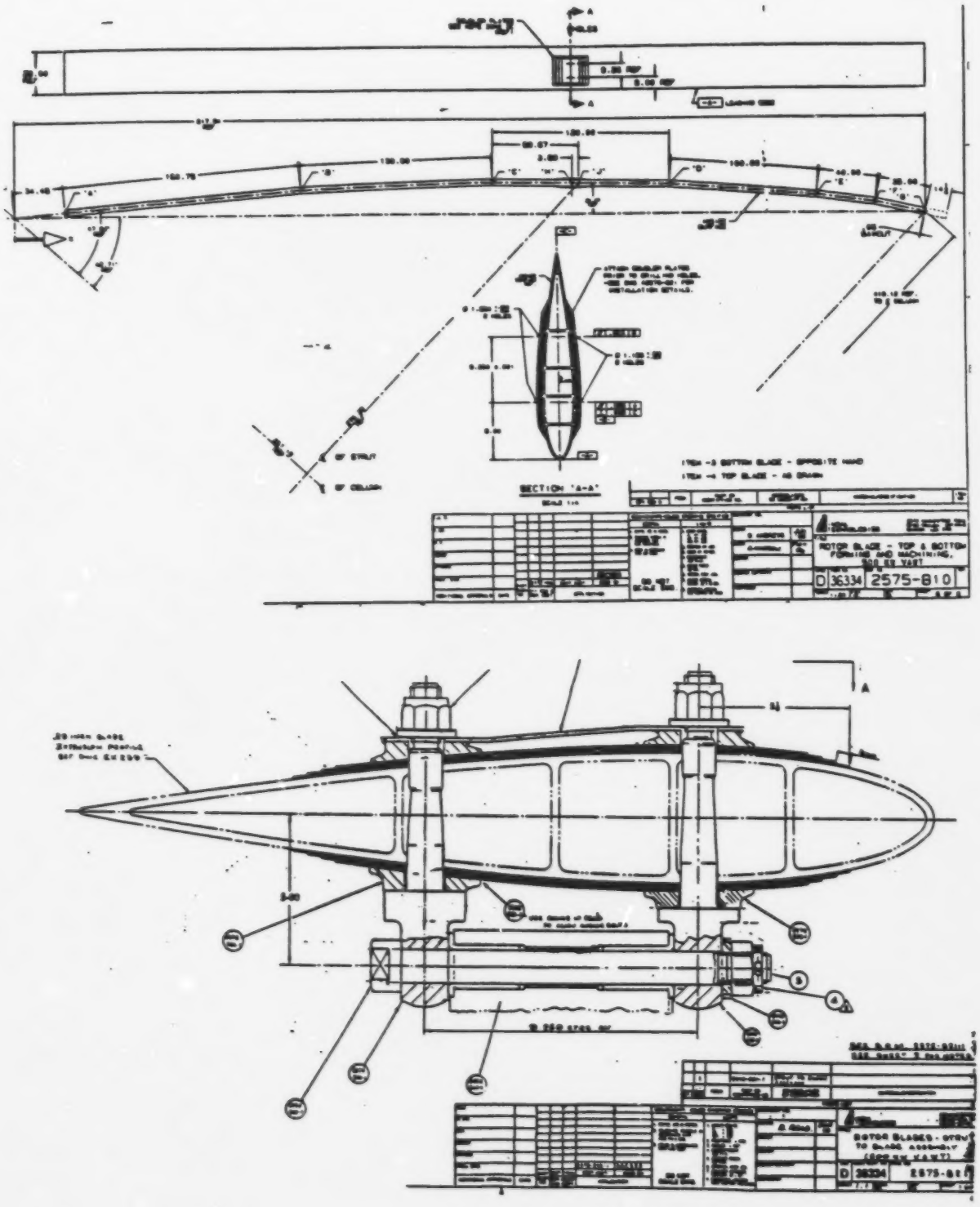


FIGURE 4

2.0 OBJECTIVES

This Research and Development Program had the following objectives.

1. Allow the rotor to be reconstructed and to operate continuously.

2. Reduce the fatigue stress levels below those in the intermediate configuration and, if possible, below those in the original configuration.

3. Simplify the design of the horizontal struts and eliminate any moving parts.

4. Offer a less expensive and more reliable strut design.

5. Monitor the response of the modified rotor and draw conclusions concerning the effectiveness of the modifications.

3.0 NEW ROTOR CONFIGURATION

3.1 Struts

The most significant change in the rotor is the struts, which are flexible I-beams and are much simpler than the damper beams installed in the original configuration. This is an attractive modification since the stepped I-beam is easily made (Figure 3). Great care was taken when the flanges were flame cut to preserve the surface finish and to ensure maximum fatigue life from the I-beam.

Modifications were also made to the hinge which is the pivot required where the blades meet the struts. The original design required that the tubes for the A-frame had to terminate at a detail which would allow the body of the hinge to bolt to it. The new hinge block takes advantage of the fact that the I-beam provides an ideal mounting location. With no further modifications or welding, it can be bolted up directly through the web.

Another difficulty experienced in the original configuration was that the strut hinge had a tendency to seize up. In order that checks could be made in the field, the new design allows the hinge to be unbolted easily to determine if it is free to move or not. In every case the dimensions of the pin and bushings have been increased, and the bushings are now made of a self-lubricating material. This material has a much higher galling threshold than did the original.

3.2 Column

The original column was retained. This meant that the strut attachment provisions required field modifications. The original rotor had a short beam running through the column perpendicular to the plane of the blades. The two ends of this beam provided the attachment for the A-frame struts. The new I-beam struts go through the column in the plane of the blades 18" further from the centre of the rotor than did the original struts and terminate in a similar fashion at the blades. The column was reinforced with 1" and 3/4" A36 steel plates around the opening in the column. This modification was performed in the field since the column was not dimensionally exact enough to make these doublers in a shop and still expect them to fit without distorting the column.

The struts were attached to the reinforced column wall with angles on both the inside and outside and on both the top and bottom of the strut. This arrangement, although difficult to assemble, avoided any eccentricity in the connection and thereby minimized local bending stresses.

3.3 Blades

The blades remain unchanged with the exception of the strut to blade detail. It was decided to strengthen this portion of the blades by bonding four 1/16-inch doublers on each side with a structural epoxy (Figure 4). The blades were first treated by etching and rinsing, followed by a coat of primer to prevent the

migration of corrosion under the epoxy. The doublers had been previously bent to the blade curvature and had been primed. Once all doublers were fitting up properly the epoxy was applied and the assembly was clamped and baked.

The final operation was the drilling/reaming operation for the hinge bolts. The holes had to be located very precisely with respect to each other, and to minimize the chance of having any stress risers the hole was reamed to final dimensions with a specially designed reamer. The holes through the blades were stepped to avoid the risk of broaching the hole in the inside face of the blade during seating of the 8" hinge bolts.

Improvement were also made to the hinge bolt and the hinge pins. In the original design these had been made from 17.4 PH heat-treated to provide the maximum tensile strength. It was decided that this design would be improved by changing from the H900 condition for these parts to H1025. This change lowered the tensile strength but improved the toughness and lowered the susceptibility to stress corrosion and fatigue crack propagation.

4.0 DATA COLLECTION

Validation of the modifications required field testing. The new rotor was installed on the original gearbox and a limited number of strain gauges were installed on the rotor - enough to be able to confirm that the structural response compared favourably with that of the previous machine. Wherever possible two bridges were applied at each location of interest. This was done so that there could be some checking as to the validity of the gauge readings. Time series from the original rotor were also available to cross-check stress readings. The gauges were connected to the NRC/AWTS data collection system and read by the NRC HSDAS (high speed data acquisition system). The gauge location and their HSDAS designator are as follows:

Channel	Code	Location
36	A7LE	blade lower root, leading edge
37	A7TE	blade lower root, trailing edge
35	A7ON	blade lower root, outer face
38	A6LE	blade, lower strut connection, leading edge
31	A6TE	blade, lower strut connection, trailing edge
33	A6IN	blade, lower strut connection, inner face
26	RCO	column, central out-of-plane bending
28	SDBR	blade, lower strut connection, outer face doubler

The calibration/set-up of the amplifiers and A-to-D converter was done very accurately and should not vary substantially based on Hewlett Packard's specifications. The voltage drop in the leads was compensated for in the gain/excitation calculation and calibration factors used are values supplied by NRC (Ref. TM-WE-028/J. Keller).

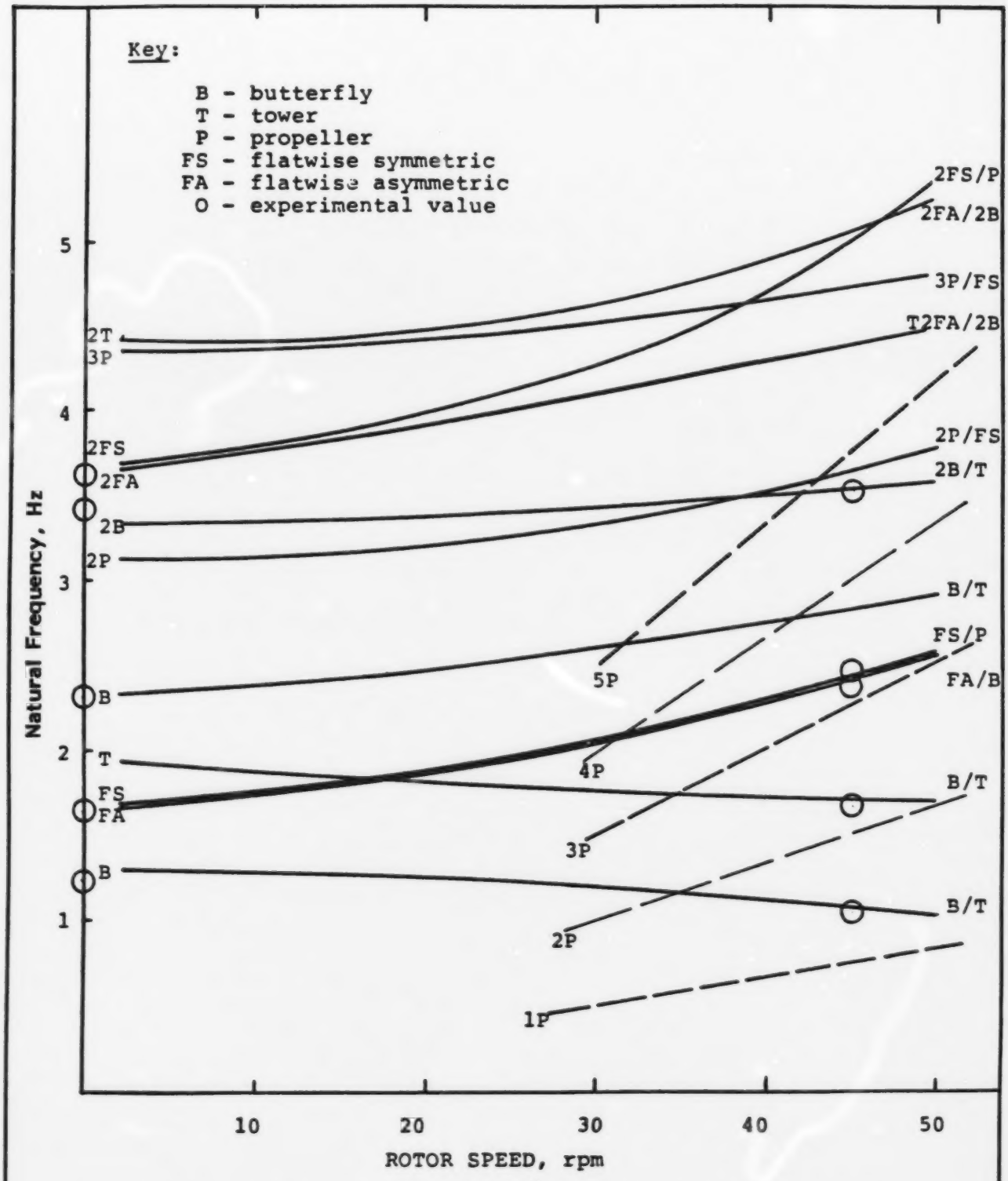


Figure 5 Natural Frequency vs. Rotor Speed for modified Indal 6400 at AWTS

5.0 TEST RESULTS

5.1 Natural Frequencies of Operating Rotor

The initial objective of the program was to ascertain the natural frequencies during operation at 45 rpm and to compare with the theoretical predictions. This comparison is presented below and summarized graphically in Figure 5.

MODE	PREDICTED VALUES	MEASURED VALUES
	Hz	Hz
B/T	1.08	1.04
B/T	1.71	1.66
FA/B	2.44	2.38
FS/P	2.46	2.48
B/T	2.87	
2B/T	3.56	3.53
2P/FS	3.64	

CODE: B = butterfly (out-of-plane)
T = tower (in-plane)
FA = flatwise asymmetric (in-plane)
FS = flatwise symmetric (in-plane)
P = propeller (out-of-plane)

The general agreement between measured and predicted natural frequencies is good (no more than 5% error).

5.2 Structural Response During Operation

Structural data from a total of ten sets of complete or partially complete records were collected, processed and evaluated. These records are listed as follows.

Record No.	Date	Time	Windspeed (m/s)
TS871760845.20D0	25 June 87	0	8.30
TS871760845.20D0	25 June 87	1150	8.43
TS872090918.20D0	28 July 87	0	11.19
TS872360847A.20D0	24 Aug. 87	300	11.38
TS873160939.5D00	12 Nov. 87	200	17.95
TS880481200.10D0	17 Feb. 88	840	15.98
TS880531008.10D0	22 Feb. 88	2440	9.05
TS880480936.10D0	17 Feb. 88	900	6.14
TS881129299.10D0	21 Apr. 88	184	15.23
TS881120400.10D0	21 Apr. 88	4700	8.00

The information from the frequency spectra from these records was plotted as amplitude vs. mean windspeed for the following gauges and is included in Appendix A.

Channel	Code	Location
36	A7LE	blade lower root, leading edge
37	A7TE	blade lower root, trailing edge
35	A7ON	blade lower root, outer face
38	A6LE	blade, lower strut connection, leading edge
31	A6TE	blade, lower strut connection, trailing edge

Channel	Code	Location
33	A6IN	blade, lower strut connection, inner face
26	RCO	column, central out-of-plane bending
28	SDBR	blade, lower strut connection, outer face doubler

5.3 Fatigue Life Prediction

The graphs in Appendix A include the harmonic peak values at 1P, 2P and 3P as well as the rms of the cyclic stresses. A straight dashed line has been drawn through the latter points and extrapolated to allow estimates of the fatigue life to be made. This estimate uses a program, LIFE5, developed at Indal Technologies and based on an earlier code written at Sandia National Laboratories. It assumes that at any windspeed the distribution of fatigue cycle amplitudes follows a Rayleigh distribution based on the indicated rms. It then uses Miner's rule to calculate the accumulated fatigue damage for the specified wind regime and S-N fatigue strength curve. The S-N curve developed at Indal Technologies for the root connections and blade splices was used for these calculations.

The most highly stressed region appears to be A7LE (blade lower root, leading edge) and a number of calculations were made of its fatigue strength. They are summarized below:

S-N Curve	Location	Cutoff m/s	RMS Modifying Factor	Mean Windspeed m/s	Estimated Life years
DAF root*1.0	A7LE	20	0.9	7.4	37.1
" " "		18	0.9	7.4	71.3
" " "		20	0.9	8.0	26.1
DAF root*0.9	A7LE	20	0.9	7.4	17.0

NOTE:

(1) a windspeed distribution having a Weibull shape factor 1.68 has been used throughout.

(2) The AWTS at PEI has a mean windspeed = 7.4 m/s.

(3) All windspeeds are quoted at the mid-rotor height.

(4) The * symbol in the S-N curve description indicates that all stress values on that curve were multiplied by the factor that follows.

(5) The "RMS modifying factor" is a factor applied to the rms stress in calculating the Rayleigh distribution of fatigue stress amplitudes. A value of 0.9 has been found to give good agreement with field data processed by a "rainflow counting" algorithm.

5.4 Comparison of Predicted and Measured Stresses

Structural analyses of the rotor operating under ambient windspeeds of 25 and 45 mph (11.1 and 20.1 m/s)

were carried out. These analyses used MSC/NASTRAN solution 30 and incorporated the rotating frame effects in the same manner as did the eigenvalue extraction. The aerodynamic model used for generating the dynamic loads was a double multiple stream tube model which included a dynamic stall routine (with the Masse-Templin modification) and corrections for Reynolds number. NRC dataset #13 (for a NACA0018 profile) was used for lift and drag coefficients.

The results of these analyses are summarized in Tables 1 and 2 for the lower root, lower strut, doubler plates and column locations. Values are presented at the 1P, 2P and 3P frequencies and a standard deviation (S), or rms of cyclic stresses, is calculated as the root of one half of the squares of those harmonics.

Where possible, the graphs in Appendix A, which summarize field data, have been used to supply mean values of the harmonic peaks as well as the rms. However, the paucity of field data, especially at windspeeds greater than 15 m/s, made such estimates difficult or impossible for some gauge locations.

Tables 1 and 2 also include field and model data, where available, for the original configuration (rigid strut with out-of-plane springs) and for the intermediate configuration (rigid, locked struts but additional blade ballast). The last column of these tables confirms the high lead-lag bending that took place adjacent to the struts in the intermediate configuration which existed at the time of the fatigue failure.

TABLE 1. Comparison of Predicted and Measured Stresses
V = 25 mph. (11.1 m/s)

		Present Configuration				Orig. Config.	Intermed. Config.
LOCATION		1P	2P	3P	S	S	S
A7LE	calculated	695	69	167	510	250	
	field	804	260	250	804	400	
A7TE	calculated	416	123	200	339	250	
	field	770	280	250	600	450	
A7IN	calculated	330	51	6	236	50	
	field					200	
A7ON	calculated	328	65	12	237	50	
	field	150			140	150	
A6LE	calculated	632	185	135	475	300	
	field	650		250	650	750	800
A6TE	calculated	204	231	163	246	280	
	field	350		200	400	550	800
A6IN	calculated	199	91	111	174	300	
	field	300			350	300	400
A6ON	calculated	817	87	109	586	300	
	field				650	350	550
SDBR	calculated	592	63	79	424		
	field						
RCI	calculated	0	972	0	694		
	field						
RCO	calculated		720		514		
	field				500		

S = Standard Deviation of Stresses
All Stress Values are in psi (MPA * 0.006894)

TABLE 2. Comparison of Predicted and Measured Stresses
V = 45 mph. (20.1 m/s)

	Present Configuration				Orig. Config.	Intermed. Config.
LOCATION	1P	2P	3P	S	S	S
A7LE calculated	1415	156	1062	1274	980	
field	1570	603	500	1574	1150	
A7TE calculated	1031	193	1285	1200	1070	
field	1300	500	350	1335	935	
A7IN calculated	483	119	512	512	250	
field					520	
A7ON calculated	697	140	408	587	250	
field	300			370	400	500
A6LE calculated	1165	523	964	1133	1430	
field				1200	1450	2400
A6TE calculated	792	653	1167	1102	1480	
field				850	1200	2550
A6IN calculated	174	127	431	355	825	
field					880	880
A6ON calculated	1268	116	407	952	1100	
field				1100	1150	1150
SDBR calculated	919	84	295	690		
field				700		
RCI calculated	0	1778	0	1380		
field						
RCO calculated	0	1238	0	932		
field				1100		

S = Standard Deviation of Stresses
All Stress Values are in psi (MPA * 0.006894)

6.0 CONCLUSIONS

(1) The introduction of flexible struts has successfully reduced the blade stresses in the region of the strut attachments. The bonded doubler plates have further reduced the blade stresses in the region of the strut attachment bolts so that the fatigue life of this detail should approach infinity.

(2) The reduction of blade stresses at the strut attachment has resulted in some increase in bending stresses at the root connections which are now the probable critical locations. However, the predicted life of this detail is still 17 years in the PEI wind regime even when some allowance for environment degradation is included.

(3) The measured natural frequencies of the operating rotor agree very closely with predicted values.

(4) Any future rotors of this type should incorporate a slightly stiffer I-beam strut in order to equalize blade bending stresses between the strut attachment region and the root connection.

(5) The limited and incomplete nature of the field data has made a reliable comparison with the mathematical predictions difficult or impossible for most strain gauge locations. However, some trends are apparent.

(6) The intermediate configuration did result in unacceptably high blade stresses adjacent to the struts. These have been successfully attenuated by the incorporation of flexible struts.

(7) The presence of the bonded doubler sheets at the strut-blade connection has further reduced the blade stresses due to in-plane bending. If these doublers do not separate, then this technique should be considered for other connections.

APPENDIX A

Summaries of spectral peaks at harmonic frequencies and rms stresses from field data

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ENGINEERING WORK SHEET

TITLE/SUBJECT Indal 6400 / AWTS Channel 36. Location ATLE

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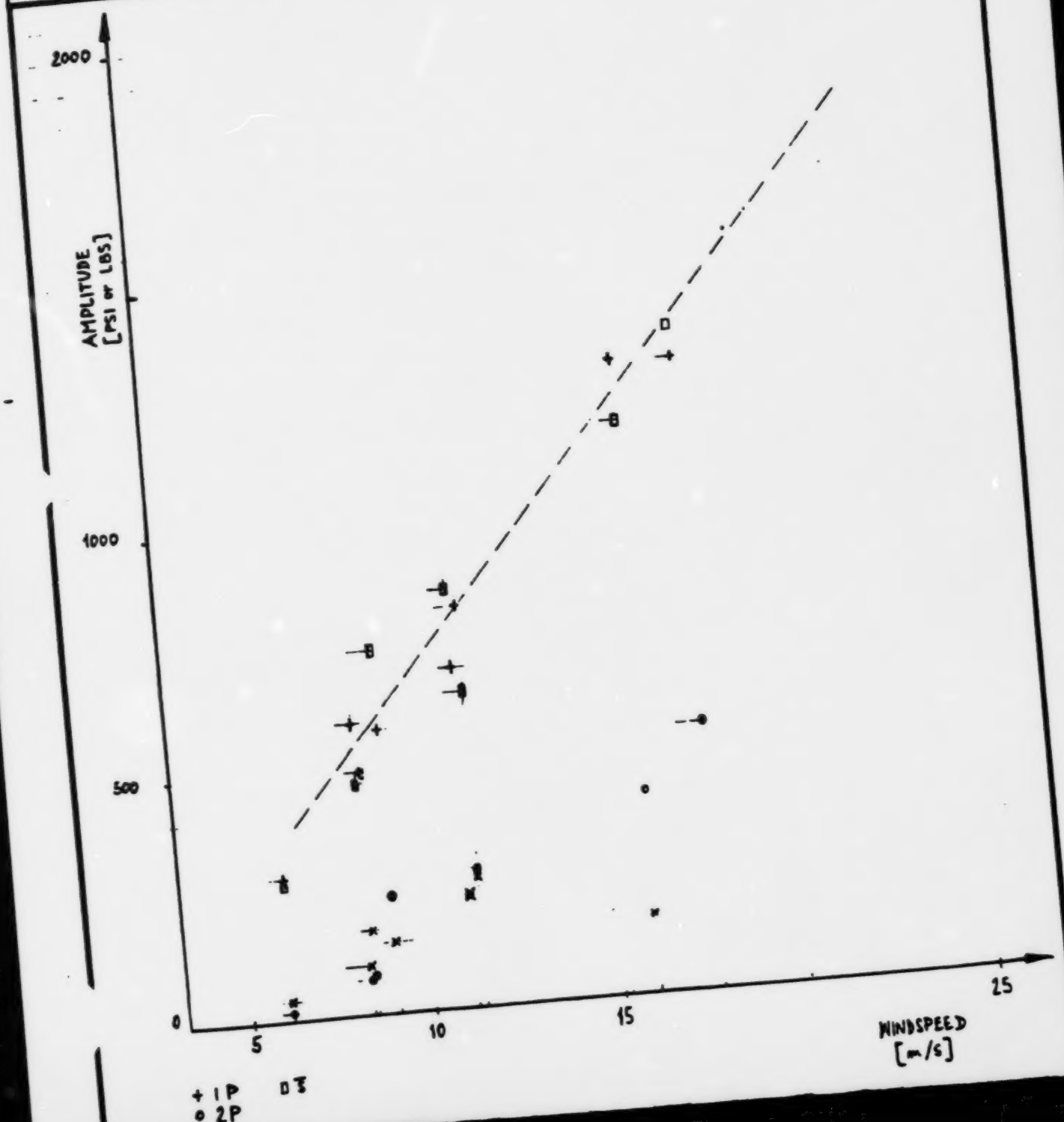

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TITLE/SUBJECT Indal 6400 / AWTS channel 57 . Location A7TE

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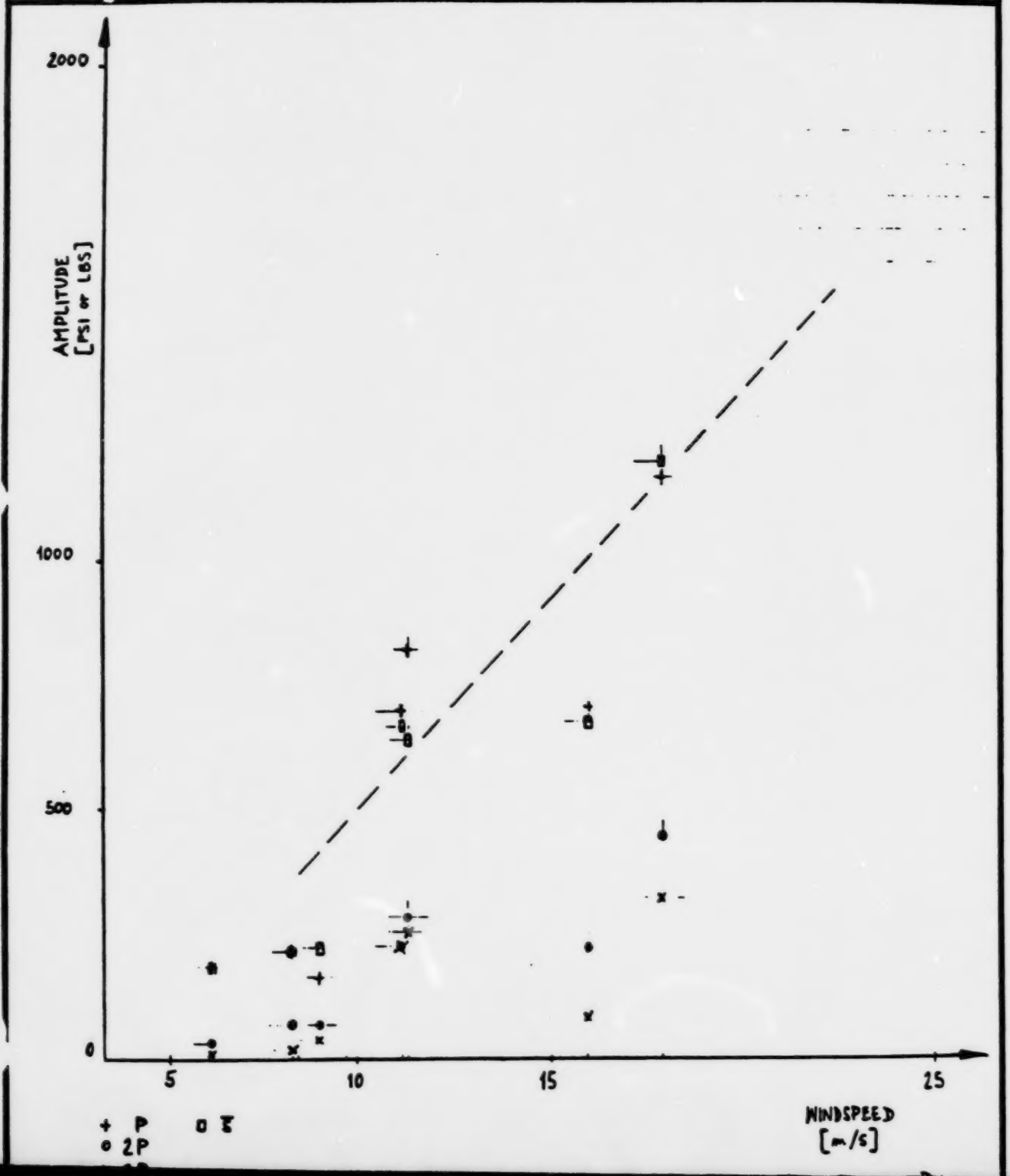

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ENGINEERING WORK SHEET

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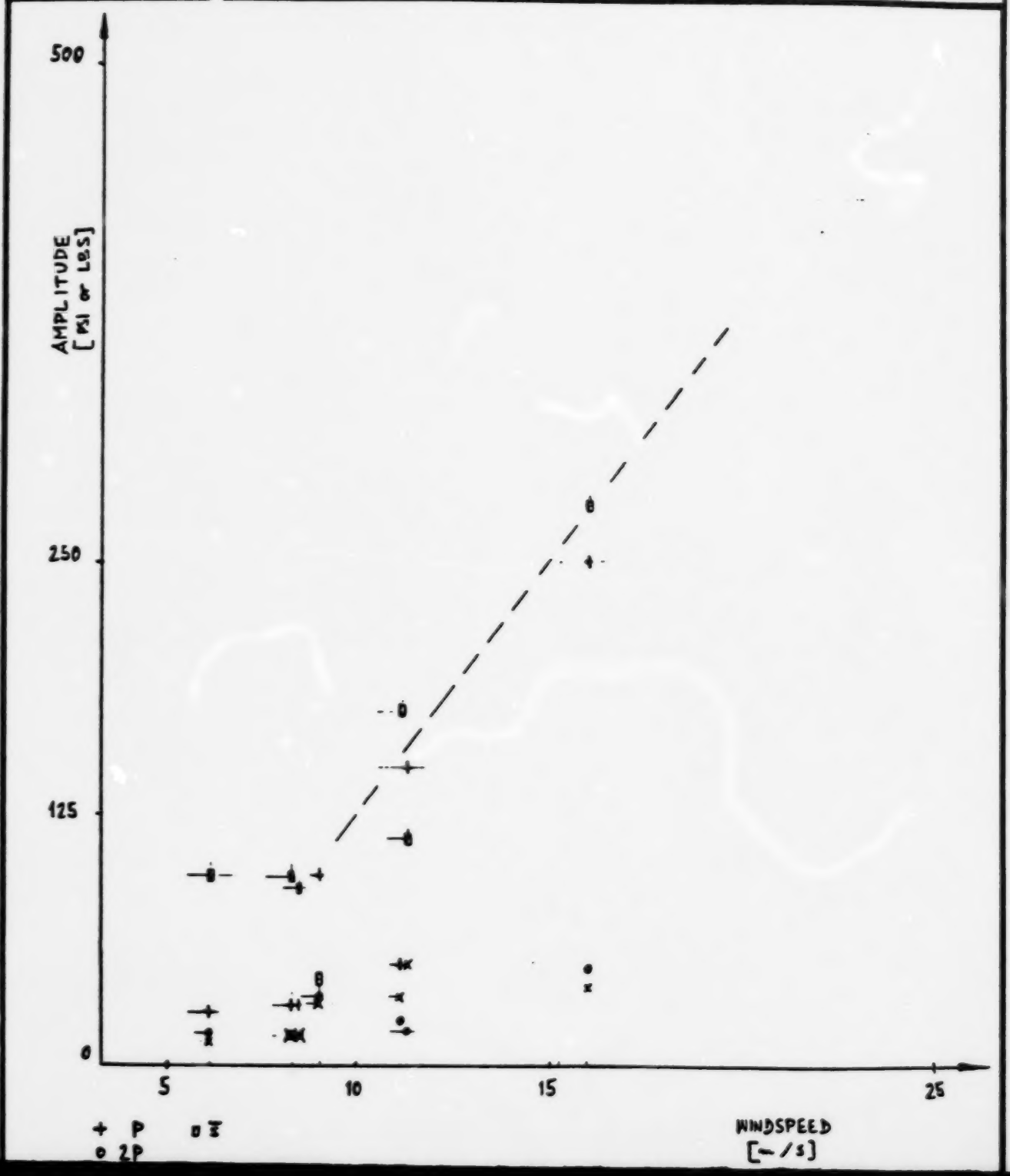

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ENGINEERING WORK SHEET

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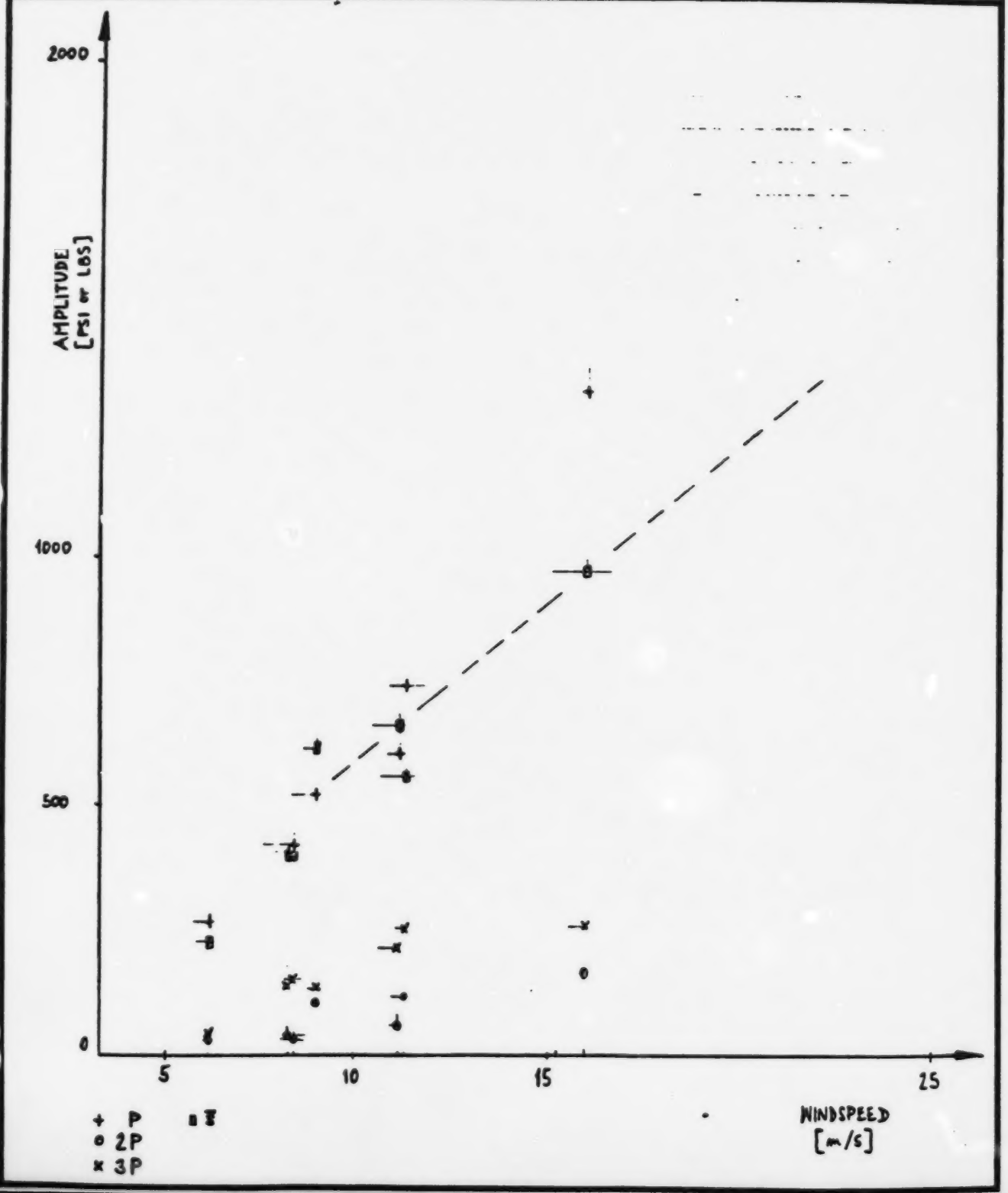

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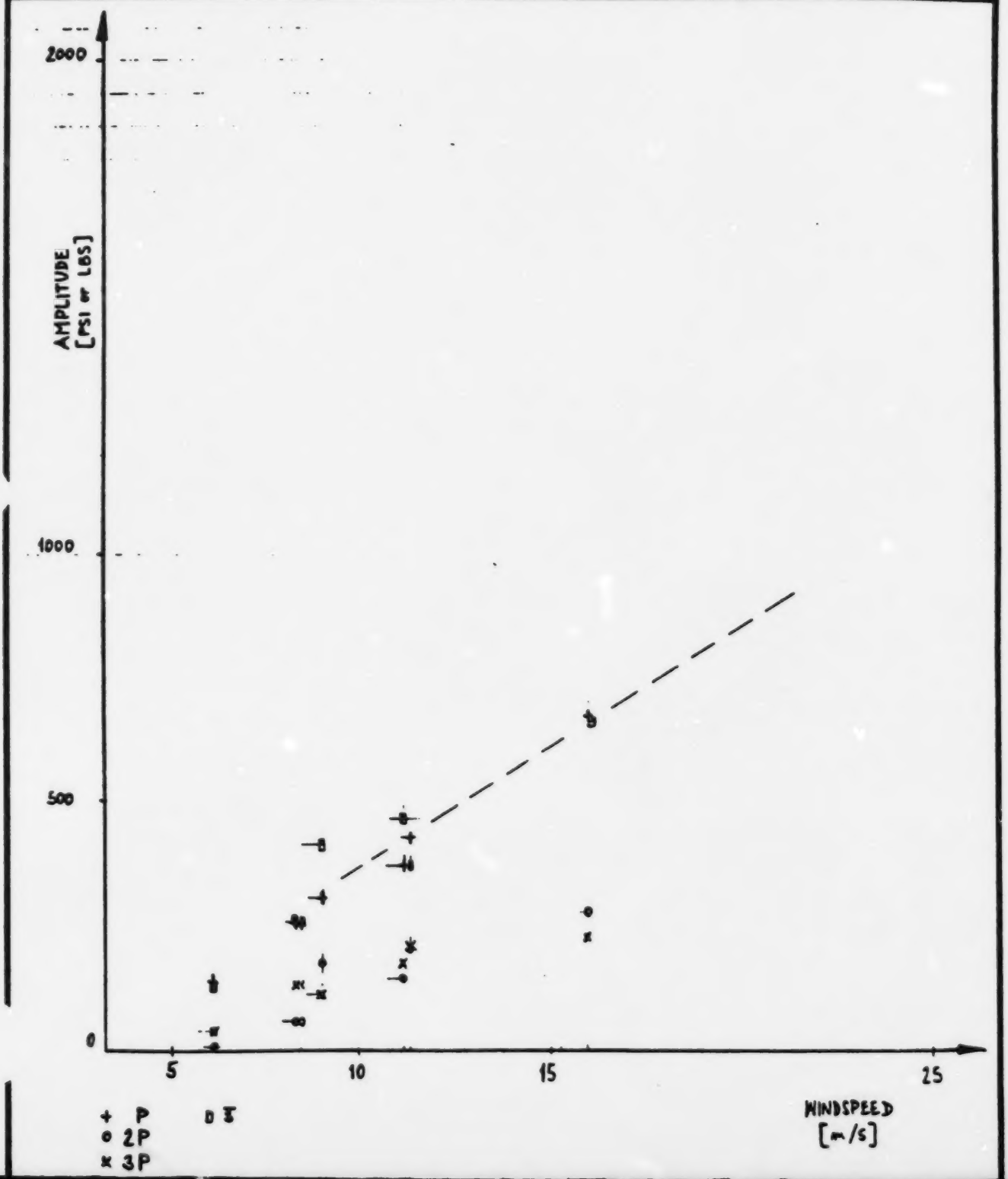

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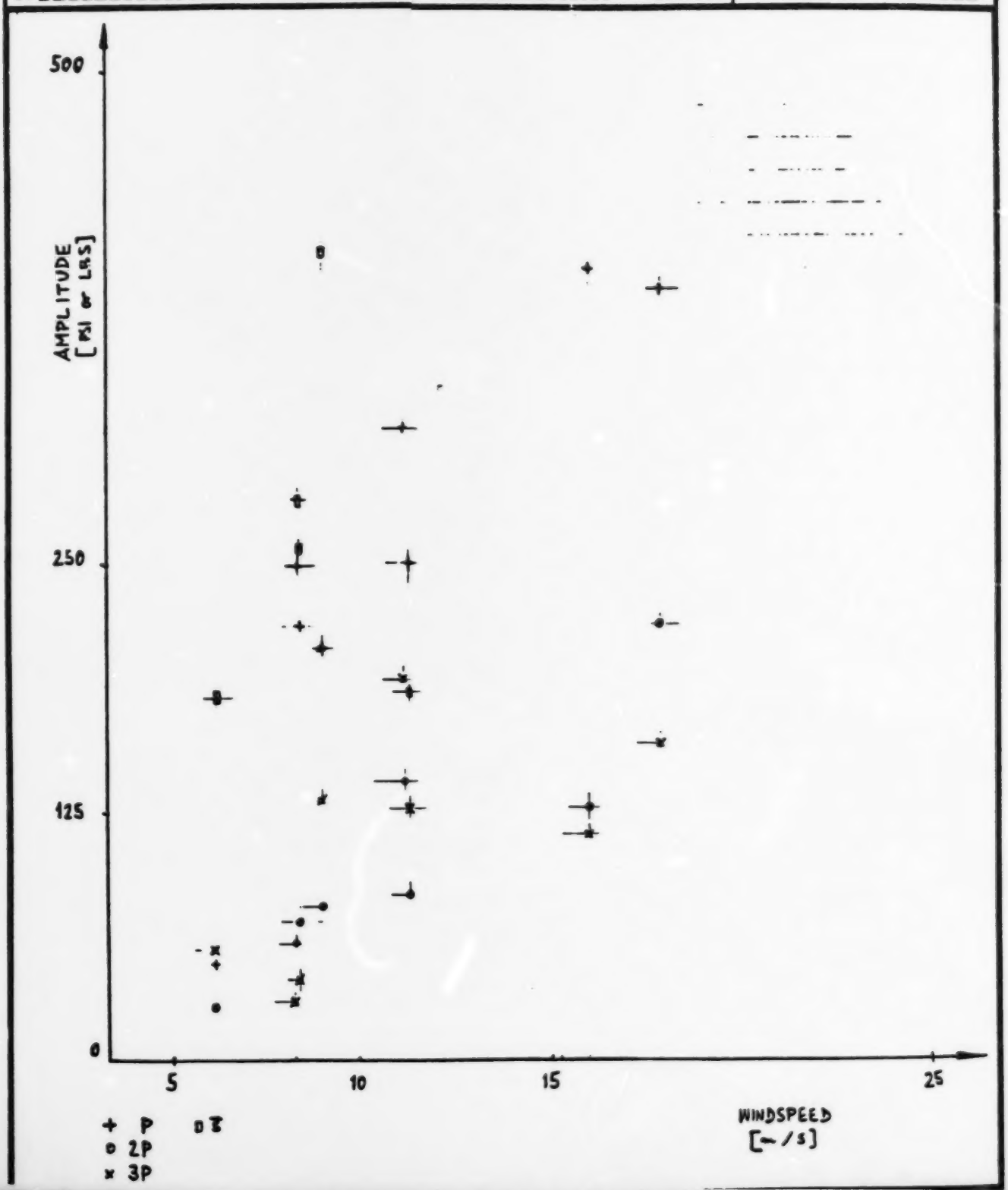

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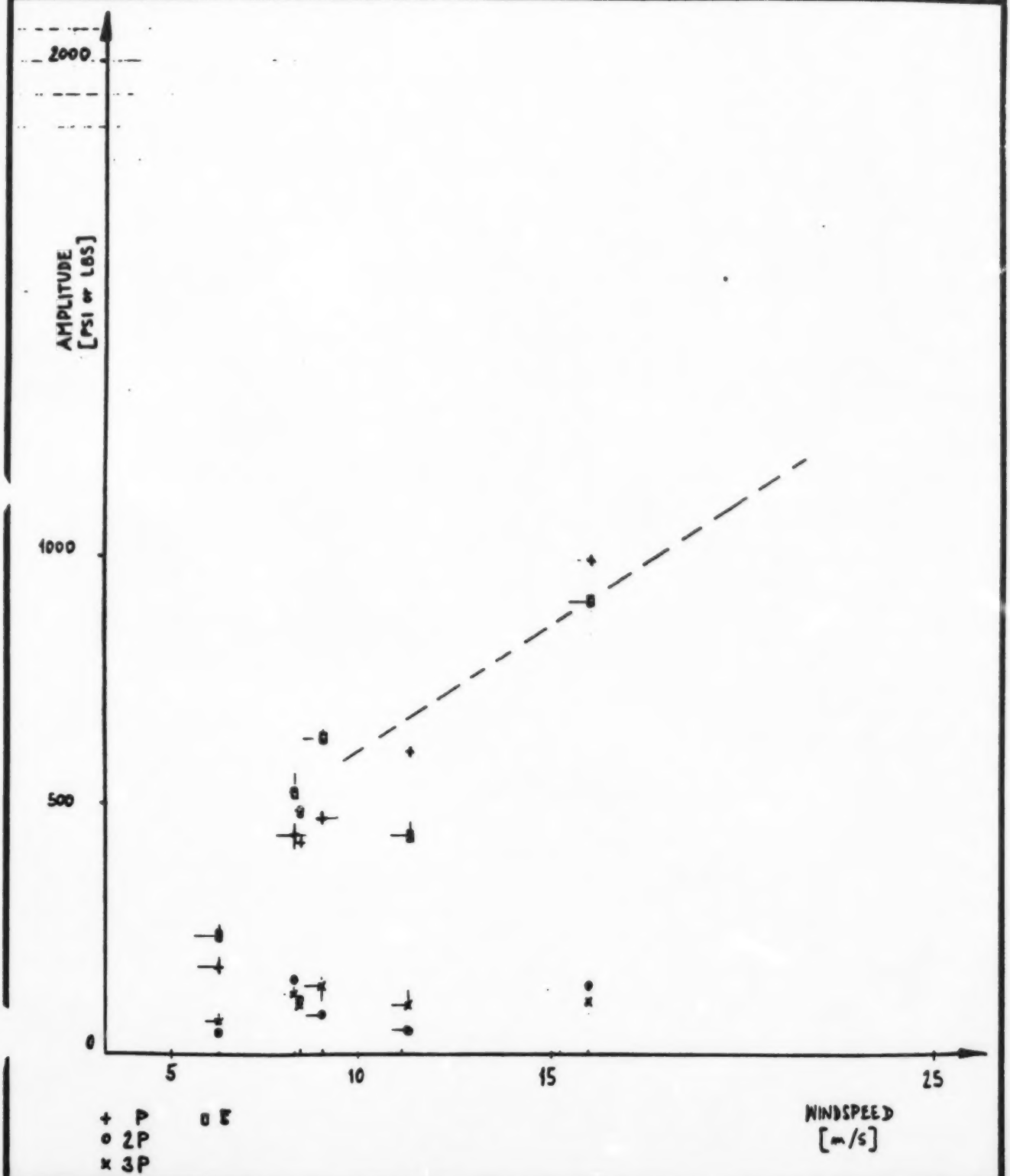

Indal Technologies Inc.

ENGINEERING WORK SHEET

TITLE/SUBJECT ____ Indal 6400/AWTS
Channel 25. Location RCI

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DOCUMENT NO. _____
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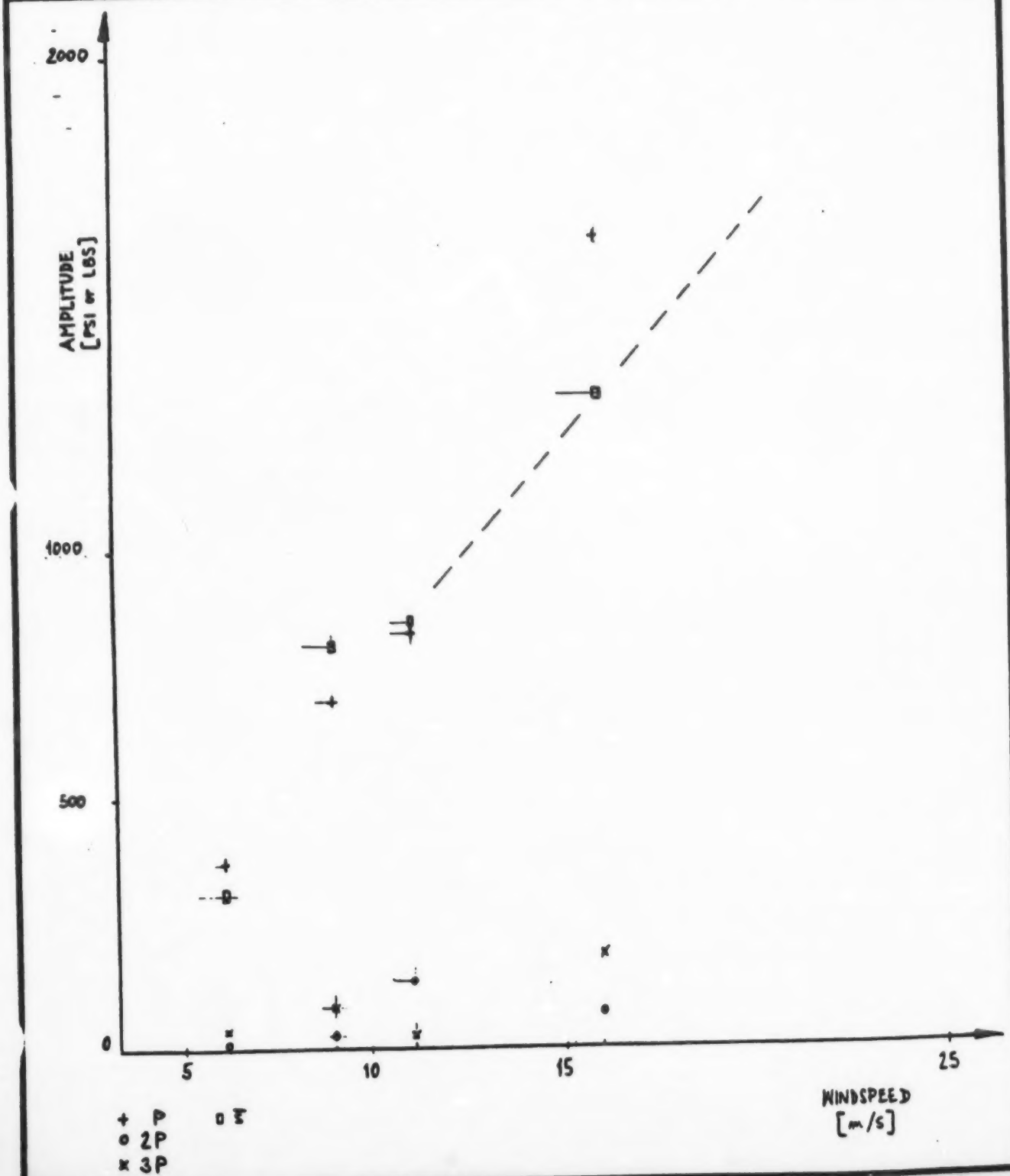
BY G. RABALSKI DATE 15.01.88 CHECKED _____ DATE _____



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ENGINEERING WORK SHEET

TITLE/SUBJECT _ Indal 6400 /AWTS
channel 26 · Location RCO

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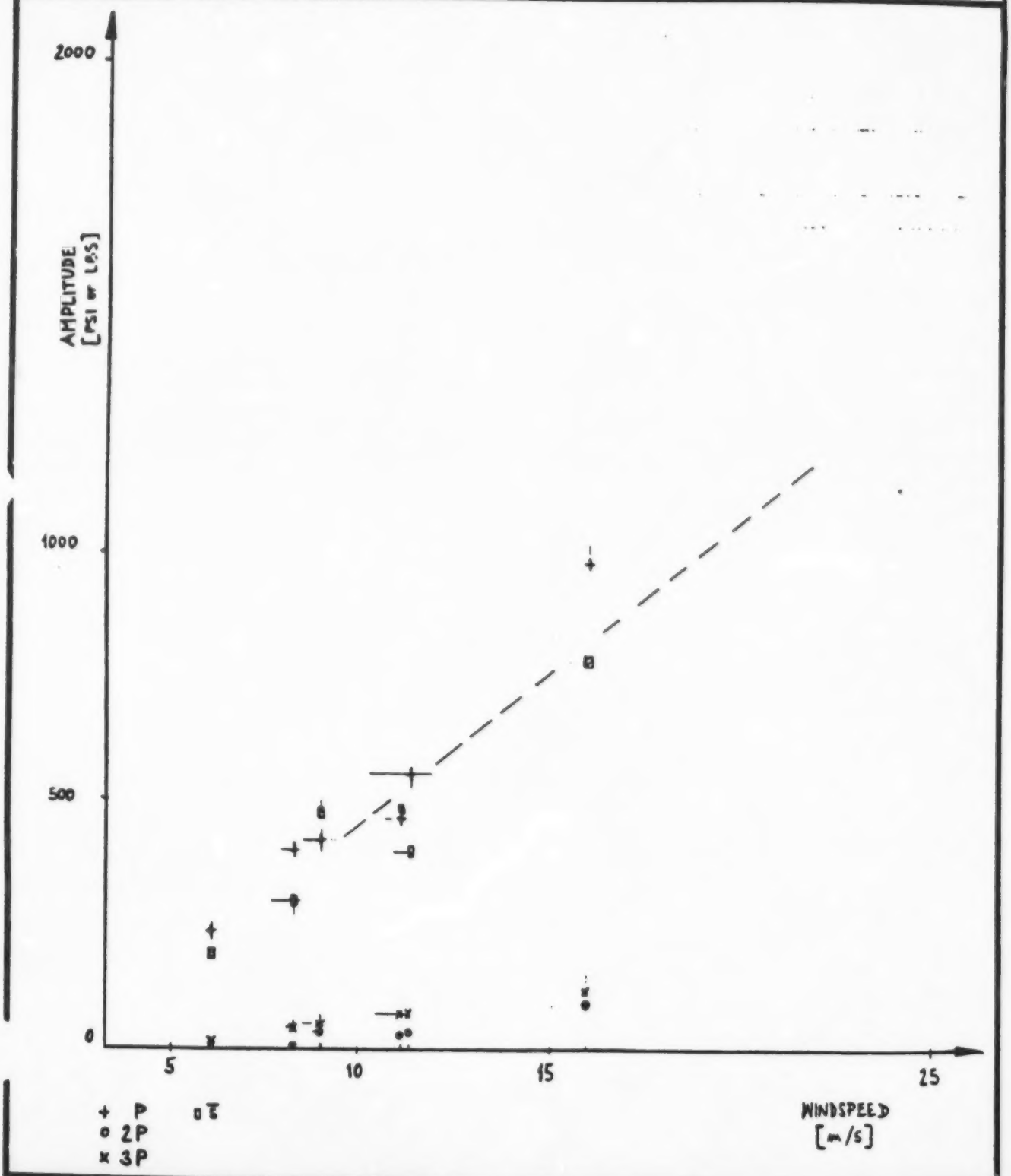

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TITLE/SUBJECT Indal 6400 / AWTS Channel 28. Location SDBR

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